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(54) **Title:** SUPERCONDUCTING MAGNET WITH COLD HEAD THERMAL PATH COOLED BY HEAT EXCHANGER

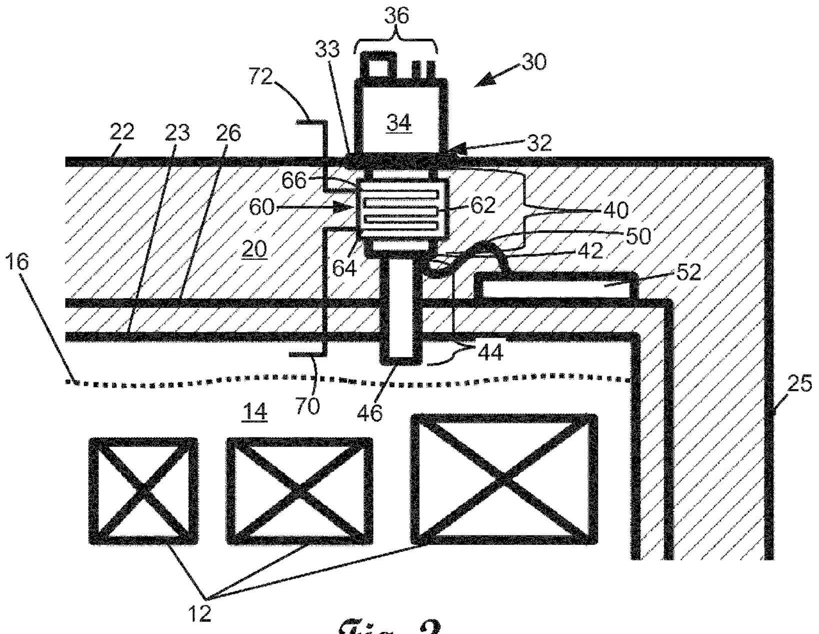

Fig. 2

(57) **Abstract:** A superconducting magnet includes a liquid helium reservoir (14), superconducting magnet windings (12) disposed in the liquid helium reservoir, and a vacuum jacket (20) surrounding the liquid helium reservoir. A cold head (30) passes through the vacuum jacket. The cold head has a warm end (32) welded to an outer wall (22) of the vacuum jacket and a cold station (46) disposed in the liquid helium reservoir. A heat exchanger (60) is disposed inside the vacuum jacket and secured to or integral with the cold head. The heat exchanger includes a fluid passage (62) having an inlet (64) in fluid communication with the liquid helium reservoir and having an outlet (66) in fluid communication with ambient air. While the cold head is turned off, gas helium flows from the liquid helium reservoir to ambient air via the heat exchanger, thereby cooling the non-operating cold head.

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SUPERCONDUCTING MAGNET WITH COLD HEAD THERMAL PATH COOLED BY HEAT EXCHANGER

FIELD

The following relates generally to the superconducting magnet arts, magnetic resonance imaging (MRI) arts, thermal management arts, and related arts.

BACKGROUND

In a typical superconducting magnet for a magnetic resonance imaging (MRI) system, the superconducting windings are immersed in liquid helium (LHe) contained in a LHe reservoir surrounded by a vacuum jacket. A high conductivity thermal shield of sheet material is disposed in the vacuum jacket to surround the LHe reservoir. After manufacture, the vacuum is drawn and the LHe reservoir is filled with LHe. To maintain the LHe at cryogenic temperature (i.e. below 4K), a cold head is used to provide refrigeration to the LHe vessel. The first stage of the cold head penetrates through into the vacuum volume, and the first stage cold station is connected to the thermal shield by a high thermal conductance link that connects with a thermal bus attached to the thermal shield. The second stage of the cold head continues into the LHe volume to be disposed in the gaseous He overpressure above the LHe level in the LHe reservoir. During shipment, the cold head is turned off and the magnet is shipped with the LHe charge loaded. With the cold head off, the vacuum jacket is relied upon to provide sufficient thermal insulation to maintain the LHe charge in its liquid state during shipping.

The following discloses a new and improved systems and methods.

SUMMARY

In one disclosed aspect, a superconducting magnet includes a liquid helium reservoir, superconducting magnet windings disposed in the liquid helium reservoir, and a vacuum jacket surrounding the liquid helium reservoir. A cold head passes through the vacuum jacket. The cold head has a warm end welded to an outer wall of the vacuum jacket and a cold station disposed in the liquid helium reservoir. A heat exchanger is disposed inside the vacuum jacket and secured to or integral with the cold head. The heat exchanger includes a fluid passage having an inlet in fluid communication with the liquid helium reservoir and having an outlet in fluid communication with ambient air.

In a disclosed method aspect utilizing the foregoing superconducting magnet, while the cold head is turned off, gas helium flows from the liquid helium reservoir to ambient air via the heat exchanger, thereby cooling the non-operating cold head. Thus, for example, during transport of the superconducting magnet while the cold head is turned off, the flowing of gas helium from the liquid helium reservoir to ambient air via the heat exchanger reduces helium boil-off during the transport.

In another disclosed aspect, a cold head comprises: a first stage section having a warm end and an opposite end defining a first stage cold station; a second stage section having a proximate end connected with the first stage cold station and a distal end defining a second stage cold station; and a heat exchanger secured to or integral with at least the first stage section. The heat exchanger includes a fluid passage having an inlet and an outlet.

One advantage resides in providing a superconducting magnet with reduced liquid helium (LHe) boil-off.

Another advantage resides in providing a superconducting magnet with reduced likelihood of quench during extended intervals over which the cold head is shut off.

Another advantage resides in providing a superconducting magnet that can be shipped over longer distances with a LHe charge.

Another advantage resides in providing a superconducting magnet that can have its cold head shut off for more extended time intervals to facilitate longer-distance shipping, extended maintenance, or so forth.

Another advantage resides in providing a superconducting magnet with reduced liquid helium evaporation during intervals over which the cold head is turned off or is non-operational.

A given embodiment may provide none, one, two, more, or all of the foregoing advantages, and/or may provide other advantages as will become apparent to one of ordinary skill in the art upon reading and understanding the present disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of illustrating the preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 diagrammatically illustrates a side sectional view of a magnetic resonance imaging (MRI) system including a cold head with a heat exchanger secured to or integral with the first stage of the cold head.

FIGURE 2 diagrammatically illustrates an enlarged view of the portion of the side sectional view of FIGURE 1 depicting the cold head and heat exchanger.

FIGURE 3 diagrammatically illustrates the enlarged view of FIGURE 2 with a variant embodiment in which the heat exchanger is secured to or integral with both the first stage and the second stage of the cold head.

FIGURE 4 diagrammatically illustrates a process for charging the superconducting magnet of FIGURE 1 with liquid helium (LHe) and transporting it from the factory to a destination.

DETAILED DESCRIPTION

As previously noted, after filling the LHe reservoir, the cold head is turned off and the MR magnet is shipped, with the LHe charge loaded and the vacuum drawn, to the destination. If shipped by air, the cold head remains off during the entire shipping time interval. If transported by ship, the MR magnet may be refrigerated; however, even in this case there are extended time intervals during loading and offloading and trucking to and from the shipyard during which the cold head is shut off. When not actively refrigerated, the LHe slowly boils off, e.g. via a provided vent path such as a helium vent bellow.

The cold head typically comprises a stainless steel cylinder containing a motor-operated displacer executing a refrigeration cycle, e.g. using gas helium as a working cryogenic fluid, and an internal copper screen. The cold head installed on the magnet passes through the vacuum jacket, and has a warm end welded to an outer wall of the vacuum jacket and a cold station disposed in the liquid helium reservoir. In a commonly employed two-stage cold head, there is an intermediate cold station located at an intermediate position between the warm end and the cold station disposed in the liquid helium reservoir, e.g. inside the vacuum jacket. In this configuration, the intermediate cold station is commonly referred to as the first stage cold station, while the cold station disposed in the liquid helium reservoir is referred to as the second stage cold station. The first stage cold head is at a higher temperature than the second stage cold station (though still well below ambient temperature). During cold head operation, the refrigeration cycle operates to chill the stainless steel cylinder to cryogenic temperature, e.g. ~4K-10K in some commercially available cold heads, with the distal end in the liquid helium reservoir being chilled to the coldest temperature (thus forming the second stage cold station).

However, when the cold head stops operating, the stainless steel cylinder, and particularly the first and second stage cold stations, warms up. This creates a thermal leakage path that can conduct heat from the warm end welded to the outer wall of the vacuum jacket to the second stage cold station in the liquid helium reservoir, thereby heating the LHe. This results in more rapid boiloff of LHe. The thermal leakage path formed by the stopped cold head can therefore limit shipping distance or otherwise constrain shipping options.

Similar problems can arise any time the cold head of the superconducting magnet is shut off for an extended time period, e.g. during maintenance, an extended power outage, during relocation of the MRI system, or so forth. As the superconducting coils carry superconducting current continuously, LHe loss has the potential to lead to a transition out of the superconducting state, referred to as a "quench" of the MR magnet.

In improvements disclosed herein, a heat exchanger is secured to the cold head (or, alternatively, may be formed integral with the cold head, e.g. integrated into the stainless steel cylinder). The heat exchanger has an inlet connected via a pipe or other fluid conduit to the gas helium overpressure in the LHe reservoir, and an outlet that discharges into the ambient. Thus, gas He (which, within the LHe reservoir, is at a low temperature close to the boiling point of LHe, i.e. ~4K) flows through the heat exchanger before venting to atmosphere, thereby cooling the cold head and reducing or eliminating the thermal leakage path presented by the cold head. This has the benefit of leveraging the sensible cooling capacity of the cold gas He to provide continued cooling of the cold head (and more particularly its stainless steel cylinder housing) over time intervals when the cold head is turned off.

With reference to FIGURE 1, a side sectional view is shown of a magnetic resonance imaging (MRI) device **10**, which employs a superconducting magnet. The magnet includes superconducting windings **12** disposed in a liquid helium (LHe) reservoir **14** which is mostly filled with LHe; however, there is a gaseous helium (gas He) overpressure present above the LHe level **16**. The illustrative MRI device **10** employs a horizontal-bore magnet in which the superconducting magnet is generally cylindrical in shape and surrounds (i.e. defines) a horizontal bore **18**; however, other magnet geometries are also contemplated. To provide thermal isolation of the LHe reservoir **14**, a vacuum jacket **20** surrounds the LHe reservoir **14**. The vacuum jacket **20** includes an outer wall **22** and an inner wall **23**. The illustrative inner wall **23** is shared between the LHe reservoir **14** and the vacuum jacket **20** (i.e. forms the boundary between the LHe reservoir **14** and vacuum jacket **20**). In an alternative embodiment, the LHe reservoir and vacuum jacket can have separate walls at this boundary that are welded together or otherwise coincident). The vacuum jacket **20** further includes side walls **24**, **25** or the like sufficient to provide vacuum-tight sealing of its ends. The vacuum volume contained by the vacuum jacket **20** is diagrammatically indicated in FIGURE 1 by hatching. A thermal shield **26** made of a sturdy thermally conductive material such as aluminum alloy sheet metal (or copper alloy sheet metal or some other high thermal conductivity sheet metal) is preferably disposed in the vacuum volume (that is, inside the vacuum jacket **20**) and surrounds the LHe reservoir **14**. The thermal shield **26** is spaced apart from the inner vacuum jacket wall **23** to avoid thermal conduction from the thermal shield **26** into the LHe reservoir **14**. In some embodiments, the thermal shield **26** may comprise two or more thermal shield layers (variant not shown) spaced apart from each other and with the innermost shield layer spaced apart from the inner vacuum jacket wall **23**.

With continuing reference to FIGURE 1 and with further reference to FIGURE 2, a cold head **30** executes a refrigeration cycle using a working fluid such as helium to provide active cooling of the LHe reservoir **14** and, in the illustrative embodiment, also provides active cooling of the thermal shield **26**. The cold head **30** passes through the vacuum jacket **20**. A warm end **32** of the cold head **30** is welded to the outer wall **22** of the vacuum jacket by one or more welds **33**. (Note, some features of the cold head **30** are labeled with reference numbers only in the enlargement shown in FIGURE 2). A motorized drive assembly **34** is connected to the warm end **32** of the cold head **30** (and may be viewed as part of the warm end), and includes a motor that drives a displacer (internal components not shown) to cause cyclic compression and expansion of the working fluid in accord with a refrigeration cycle. At least a distal end of the motorized drive assembly **34** is outside of the vacuum jacket **20** and hence exposed to ambient air, and this exposed end includes connectors **36** for attachment of one or more electrical power cables and one or more hoses for injecting the working fluid (cables and hoses not shown). The illustrative cold head **30** is preferably a cylindrical cold head, although other geometries are contemplated.

The illustrative cold head **30** is a two-stage design that includes: a first stage section **40** having one end being the warm end **32** and an opposite end defining an intermediate (or first stage) cold station **42**; and a second stage section **44** connected with the intermediate (or first stage) cold station **42** and penetrating into the liquid helium reservoir **14** to define a second stage cold station **46** disposed in the liquid helium reservoir **14**. The first stage section **40** and the second stage section **44** each comprise a stainless steel cylinder housing through which the displacer passes, with the second stage section **44** typically having a smaller diameter than the first stage section **40**. (That is, the first stage section **40** is cylindrical with a first diameter and the second stage section **44** is cylindrical with a second diameter smaller than the first diameter). The penetration of the second stage section **44** through the inner wall **23** is suitably sealed using an annular weld or other vacuum-tight seal.

The first stage cold station **42** is connected with the thermal shield **26** by a high conductance thermal link **50** that connects with a thermal bus **52** that is welded, brazed, or otherwise secured to the thermal shield **26**. The second stage cold station **46** is disposed in gaseous He overpressure above the LHe level **16** in the LHe reservoir **14**. The cold head **30** is designed and operated to cool the second stage cold station **46** to below the liquefaction temperature of helium, and the first stage cold station **42** to a higher temperature (albeit cool enough for the thermal shield **26** to provide effective thermal shielding of the LHe reservoir **14**). To provide vacuum-tight seals, the cold head **30** is typically welded to the outer vacuum wall **22** and to the inner vacuum wall **23**.

To operate the superconducting magnet, a LHe charge is loaded into the LHe reservoir **14** via a suitable fill line (not shown). The fill line or another ingress path also provides for inserting electrical conductive leads or the like (not shown) for connecting with and electrically energizing the magnet windings **12**. A static electric current flowing through these windings **12** generates a static B_0 magnetic field, which is horizontal as indicated in FIGURE 1 in the illustrative case of a horizontal bore magnet. After ramping the electric current in the magnet windings **12** up to a level chosen to provide the desired $|B_0|$ magnetic field strength, the contacts can be withdrawn and the zero electrical resistance of the superconducting magnet windings **12** thereafter ensures the electric current continues to flow in a persistent manner. From this point forward, the LHe charge in the LHe reservoir **14** should be maintained; otherwise, the superconducting windings **12** may warm to a temperature above the superconducting critical temperature for the magnet windings **12**, resulting in a quench of the magnet. (To provide controlled shut-down in the event the LHe charge must be removed, the leads are preferably re-inserted and the magnet current ramped down to zero prior to removal of the LHe charge).

The MRI device optionally includes various other components known in the art, such as a set of magnetic field gradient coils **54** for superimposing selected magnetic field gradients onto the B_0 magnetic field in the x-, y-, and/or z-directions, a whole-body radio frequency (RF) coil (not shown) for exciting and/or detecting magnetic resonance signals, a patient couch (not shown) for loading a medical patient or other imaging subject into the bore **18** of the MRI device **10** for imaging, and/or so forth.

The cold head **30** beneficially chills the LHe reservoir **14** when the cold head is operational. However, the cold head is occasionally turned off. This may be done intentionally to prepare for maintenance, shipping of the magnet, or so forth, or may occur unintentionally due to some malfunction. Any time the cold head is turned off for any extended period of time, it will begin to warm up and create a thermal leakage path by which heat from ambient air contacting the warm end **32** and the motorized drive unit **34** can conduct into the LHe reservoir **14**. Thus, the cold head **30** when turned off becomes a thermal liability.

With particular reference now to FIGURE 2, the thermal leakage path presented by the non-operational cold head **30** is alleviated by providing a heat exchanger **60**, which is disposed inside the vacuum jacket **20** and is secured to or integral with the cold head **30**. The heat exchanger **60** includes a fluid passage **62** having an inlet **64** in fluid communication with the LHe reservoir **14**, and having an outlet **66** in fluid communication with ambient air. To this end, in the illustrative embodiment an inlet fluid conduit **70** passes through the common wall **23** shared between the vacuum jacket **20** and the LHe reservoir **14**. The inlet fluid conduit **70** provides fluid communication between the inlet **64** of the fluid passage **62** of the heat exchanger **60** and the LHe reservoir **14**. Similarly, an outlet fluid conduit **72** passes through the outer wall **22** of the vacuum jacket **20** and provides fluid communication between the outlet **66** of the fluid passage **62** of the heat exchanger **60** and ambient air. In operation, gas helium from the LHe reservoir **14** is injected by the gas helium overpressure into the inlet fluid conduit **70** and flows through the fluid passage **62** and thence into the outlet fluid conduit **72** to be discharged into ambient air. As the gas helium flows through the fluid passage **62**, it absorbs heat from the cold head **30**.

To facilitate this heat transfer, the fluid passage **62** of the heat exchanger **60** is preferably serpentine or spirals around the cylindrical cold head **30** to provide a large contact area. Additionally or alternatively, the fluid passage **62** may be a multi-channel fluid passage, i.e. the fluid passage **62** may provide multiple paths for gas helium to flow from the inlet **64** to the outlet **66**. The heat exchanger **60** can employ any conventional heat exchanger design for enhancing this heat transfer. In one illustrative embodiment, the heat exchanger comprises a metal shell wrapped around the cold head **30**, and the fluid passage **62** is drilled, milled, or otherwise formed into this metal shell. In this approach, the metal shell provides a thermally conductive path from the fluid passage **62** to the cylindrical cold head **30**. For maximum thermal contact, the heat exchanger **60** preferably wraps around the entire circumference of the (illustrative cylindrical) cold head **30**. For manufacturing convenience, the metal shell may be divided into discrete segments, e.g. six arcuate segments each extending over a 60^{o} arc, with tube connections between inlets and outlets of neighboring segments. Instead of a metal shell, the heat exchanger **60** may employ a shell or segments of another thermally conductive material that is more flexible, such as silicon type or acrylic type thermal conductive sheeting, with the fluid passage **62** being a tube embedded into the sheeting. These are merely illustrative examples of suitable heat exchanger designs.

In another embodiment, the heat exchanger **60** is integral with the cold head **30**. For example, the cold head **30** may employ a housing made of stainless steel cylinders, e.g. a larger diameter cylinder forming the housing of the first stage section **40**, and a smaller diameter cylinder forming the housing of the second stage section **44**. In this integral design, the cylindrical stainless steel housing **40**, **44** of the cold head **30** suitably has embedded tubing forming the fluid passage **62** of the heat exchanger, and the cylindrical stainless steel housing **40**, **44** of the cold head **30** also forms the body of the heat exchanger **60**.

As another contemplated embodiment, the heat exchanger **60** may comprise stainless steel tubing that is wrapped around the cold head **30** and is welded, brazed, or otherwise secured to outer surfaces of the cylindrical stainless steel housing **40**, **44** of the cold head **30**. This approach is straightforward to manufacture or even retrofit to an existing cold head, but has less thermal transfer surface area compared with other illustrative designs.

In the embodiment of FIGURES 1 and 2, the heat exchanger **60** is secured to the first stage section **40** of the cold head **30**, but is not secured to the second stage section **44** of the cold head **30**. Since heat flows from the ambient air into the warm end **32** of the cold head **30**, providing cooling via the heat exchanger **60** of the first stage section **40** only (without also cooling the second stage section **44**) provides substantial benefit.

However, with reference now to FIGURE 3, a variant embodiment also provides cooling via the heat exchanger of the second stage section **44**. The embodiment of FIGURE 3 includes the same superconducting magnet as in FIGURE 1 and the same cold head **30** as in FIGURES 1 and 2. The embodiment of FIGURE 3 differs from that of FIGURE 2 in that, in the embodiment of FIGURE 3, the heat exchanger $\mathbf{60_1}$, $\mathbf{60_2}$ includes a first heat exchanger section $\mathbf{60_1}$ (with a first fluid passage $\mathbf{62_1}$) secured to or integral with the first stage section **40** of the cold head **30**, and also an added second heat exchanger section $\mathbf{60_2}$ (with a second fluid passage $\mathbf{62_2}$) which is secured to or integral with the second stage section **44** of the cold head **30**. The second heat exchanger section $\mathbf{60_2}$ includes the inlet **64** of the heat exchanger $\mathbf{60_1}$, $\mathbf{60_2}$ in fluid communication with the LHe reservoir via the inlet fluid conduit **70**. The first heat exchanger section $\mathbf{60_1}$ includes the outlet **66** of the heat exchanger in fluid communication with ambient air via the outlet fluid conduit **72**. The heat exchanger $\mathbf{60_1}$, $\mathbf{60_2}$ further includes a fluid conduit **74** connecting the first heat exchanger section $\mathbf{60_1}$ and the second heat exchanger section $\mathbf{60_2}$ in series. That is, the gas helium flows into the inlet **64**, through the second heat exchanger section $\mathbf{60_2}$, then through the fluid conduit **74** and into the first heat exchanger section 60_1, and finally exits from the outlet **66** of the first heat exchanger section 60_1 and discharged into ambient air.

The disclosed heat exchanger **60** has the dual benefits of providing a gas helium overpressure vent path and leveraging the sensible cooling capacity of the cold gas He in the LHe tank **14** to provide cooling of the cold head **30** over time intervals when the cold head **30** is turned off (or, more generally, not operating to provide cryogenic cooling).

The heat exchanger **60** should be helium leak-tight because any gas helium leaking out of the heat exchanger **60** will enter the vacuum contained by the vacuum jacket **20**. Excessive gas leakage into this vacuum space can compromise the thermal insulation of the LHe reservoir **14**, which in an extreme case can lead to rapid boiling of the liquid helium and potential magnet quench or damage.

With reference to FIGURE 4, a process for loading a LHe charge and transporting the superconducting magnet of the MRI device **10** of FIGURE 1 is described. Starting with the fabricated magnet, in an operation **80** the vacuum jacket **20** is evacuated using suitable vacuum couplings (not shown in FIGURE 1) on the outer vacuum wall **22**. In an operation **81**, the liquid helium reservoir **14** is evacuated. In an operation **82**, the cold head **30** is turned on and in an operation **84** the liquid helium (LHe) charge is loaded via a fill line (not shown in FIGURE 1) passing through the outer vacuum wall **22**. It will be appreciated that the operations **82**, **84** may be performed in a different order, and/or additional operations known in the art may be performed. Typically, the operation **84** entails evacuating air from the LHe reservoir **14** prior to flowing the LHe into the LHe reservoir **14**. After charging the superconducting magnet with LHe, in an operation **86** the cold head **30** is turned off preparatory to transport operation(s) **90** in which the superconducting magnet (filled with the LHe charge) is transported. During the operation(s) **90** the heat exchanger **60** operates to provide cooling of the cold head **30**, as well as to provide a vent path for overpressure of gas helium in the LHe reservoir **14**. Because the gas helium in the LHe reservoir **14** is an overpressure above the LHe level **16**, the gas helium is at a temperature above, but relatively close to, the boiling temperature of the LHe, i.e. around 4K at (close to) atmospheric pressure. Thus, even without operation of the cold head **30**, the heat exchanger **60** operates to provide a passive mechanism for cooling the non-operating cold head **30**, which in turn reduces the rate of evaporation of the LHe in the LHe reservoir **14**. This reduction in LHe evaporation rate allows for longer transport times and consequently longer achievable transport distances. After arriving at the destination, in an operation **92** the cold head **30** is turned back on, thereafter providing active cooling of the LHe reservoir **14**.

While advantages of the disclosed heat exchanger **60** thermally coupled with the cold head **30** accrue during magnet transport as described with reference to FIGURE 4, it will be appreciated that analogous benefit is obtained for any procedure or situation in which the cold head **30** is turned off or otherwise non-operational for an extended time period, e.g. while the cold head **30** is turned off during maintenance, or during extended electrical power outages, or during a malfunction of the cold head **30** that compromises or prevents active cooling via the cold head **30**, or so forth. In such situations, the reduced LHe evaporation reduces the likelihood that the LHe charge will be unduly depleted, and reduces the likelihood that LHe depletion may lead to magnet quenching.

The invention has been described with reference to the preferred embodiments. Modifications and alterations may occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

CLAIMS:

1. A superconducting magnet comprising:

a liquid helium reservoir (14);

superconducting magnet windings (12) disposed in the liquid helium reservoir;

a vacuum jacket (20) surrounding the liquid helium reservoir;

a cold head (30) passing through the vacuum jacket, the cold head having a warm end (32) welded to an outer wall (22) of the vacuum jacket and a cold station (46) disposed in the liquid helium reservoir; and

a heat exchanger (60) disposed inside the vacuum jacket and secured to or integral with the cold head, the heat exchanger including a fluid passage (62) having an inlet (64) in fluid communication with the liquid helium reservoir and having an outlet (66) in fluid communication with ambient air.

2. The superconducting magnet of claim 1 wherein the cold head (30) further includes a motorized drive assembly (34) disposed outside of the vacuum jacket (20) and connected with the warm end (32) of the cold head, the drive assembly including one or more connectors (36) exposed to ambient air.

3. The superconducting magnet of any one of claims 1-2 wherein the cold head (30) is a cylindrical cold head.

4. The superconducting magnet of any one of claims 1-3 wherein the cold head (30) includes:

a first stage section (40) having one end being the warm end (32) of the cold head and an opposite end defining an intermediate cold station (42); and

a second stage section (44) connected with the intermediate cold station and penetrating into the liquid helium reservoir (14) to define the cold station (46) disposed in the liquid helium reservoir;

wherein the heat exchanger (60) is secured to or integral with at least the first stage section.

5. The superconducting magnet of claim 4 wherein the heat exchanger (60) is secured to the first stage section (40) and is not secured to the second stage section (44).

6. The superconducting magnet of claim 4 wherein the heat exchanger includes:

a first heat exchanger section (60_1) secured to or integral with the first stage section (40) of the cold head (30); and

a second heat exchanger section (60_2) secured to or integral with the second stage section (44) of the cold head.

7. The superconducting magnet of claim 6 wherein:

the second heat exchanger section (60_2) includes the inlet (64) of the heat exchanger in fluid communication with the liquid helium reservoir (14);

the first heat exchanger section (60_1) includes the outlet (66) of the heat exchanger in fluid communication with ambient air; and

the heat exchanger (60_1, 60_2) further includes a fluid conduit (74) connecting the first heat exchanger section and the second heat exchanger section in series.

8. The superconducting magnet of any one of claims 4-7 further comprising:

a thermal shield (26) disposed in the vacuum jacket (20) and surrounding the liquid helium reservoir (14);

wherein the intermediate cold station (42) is in thermal contact with the thermal shield (26).

9. The superconducting magnet of any one of claims 1-8 wherein the heat exchanger further includes:

an inlet fluid conduit (70) passing through a common wall (23) shared between the vacuum jacket (20) and the liquid helium reservoir (14), the inlet fluid conduit providing fluid communication between the inlet (64) of the fluid passage (62) of the heat exchanger (60) and the liquid helium reservoir.

10. The superconducting magnet of any one of claims 1-9 wherein the heat exchanger further includes:

an outlet fluid conduit (72) passing through the outer wall (22) of the vacuum jacket (20) and providing fluid communication between the outlet (66) of the fluid passage (62) of the heat exchanger (60) and ambient air.

11. The superconducting magnet of any one of claims 1-10 wherein the fluid passage (62) of the heat exchanger (60) comprises one or more of a serpentine, spiral, or multi-channel fluid passage.

12. A magnetic resonance imaging (MRI) device comprising:

a superconducting magnet as set forth in any one of claims 1-11 which is generally cylindrical in shape and defines a horizontal bore (18); and

a set of magnetic field gradient coils (54) arranged to superimpose magnetic field gradients on a static magnetic field generated in the horizontal bore by the superconducting magnet.

13. A method performed in conjunction with a superconducting magnet comprising a liquid helium reservoir (14), superconducting magnet windings (12) disposed in the liquid helium reservoir, a vacuum jacket (20) surrounding the liquid helium reservoir, a cold head (30) passing through the vacuum jacket from a warm end (32) of the cold head welded to an outer wall (22) of the vacuum jacket to a cold station (46) disposed in the liquid helium reservoir, and a heat exchanger (60) disposed inside the vacuum jacket and secured to or integral with the cold head, the heat exchanger having an inlet (64) in fluid communication with the liquid helium reservoir and an outlet (66) in fluid communication with ambient air, the method comprising:

turning off the cold head; and

while the cold head is turned off, flowing gas helium from the liquid helium reservoir to ambient air via the heat exchanger.

14. The method of claim 13 further comprising:

transporting the superconducting magnet while the cold head (30) is turned off whereby the flowing of gas helium from the liquid helium reservoir (14) to ambient air via the heat exchanger (60) reduces helium boil-off during the transporting.

15. A cold head (30) comprising:

a first stage section (40) having a warm end (32) and an opposite end defining a first stage cold station (42);

a second stage section (44) having a proximate end connected with the first stage cold station and a distal end defining a second stage cold station (46); and

a heat exchanger (60) secured to or integral with at least the first stage section, the heat exchanger including a fluid passage (62) having an inlet (64) and an outlet (66).

16. The cold head (30) of claim 15 further comprising:

a motorized drive assembly (34) connected with the warm end (32) of the first stage section (40), the drive assembly including one or more operational connectors (36) exposed to ambient air.

17. The cold head (30) of any one of claims 15-16 wherein the first stage section (40) is cylindrical with a first diameter and the second stage section (44) is cylindrical with a second diameter smaller than the first diameter.

18. The cold head (30) of any one of claims 15-17 wherein the heat exchanger (60) is secured to or integral with the first stage section (40) and is not secured to or integral with the second stage section (44).

19. The cold head (30) of any one of claims 15-17 wherein the heat exchanger includes:

a first heat exchanger section (60_1) secured to or integral with the first stage section (40) of the cold head; and

a second heat exchanger section (60_2) secured to or integral with the second stage section (44) of the cold head.

20. The cold head (30) of claim 19 wherein:

the second heat exchanger section (60_2) includes the inlet (64) of the heat exchanger;

the first heat exchanger section (60_1) includes the outlet (66) of the heat exchanger; and

the heat exchanger further includes a fluid conduit (74) connecting the first heat exchanger section and the second heat exchanger section in series.

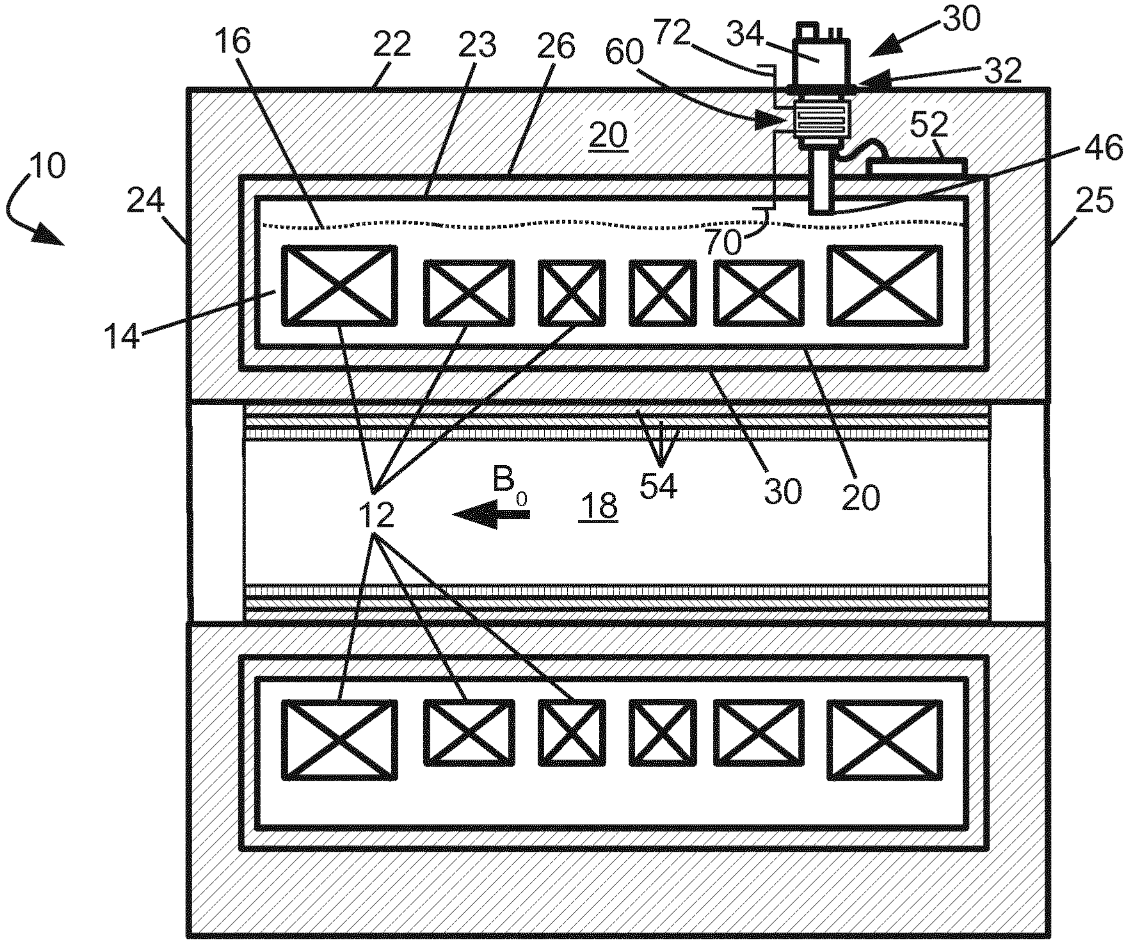

Fig. 1

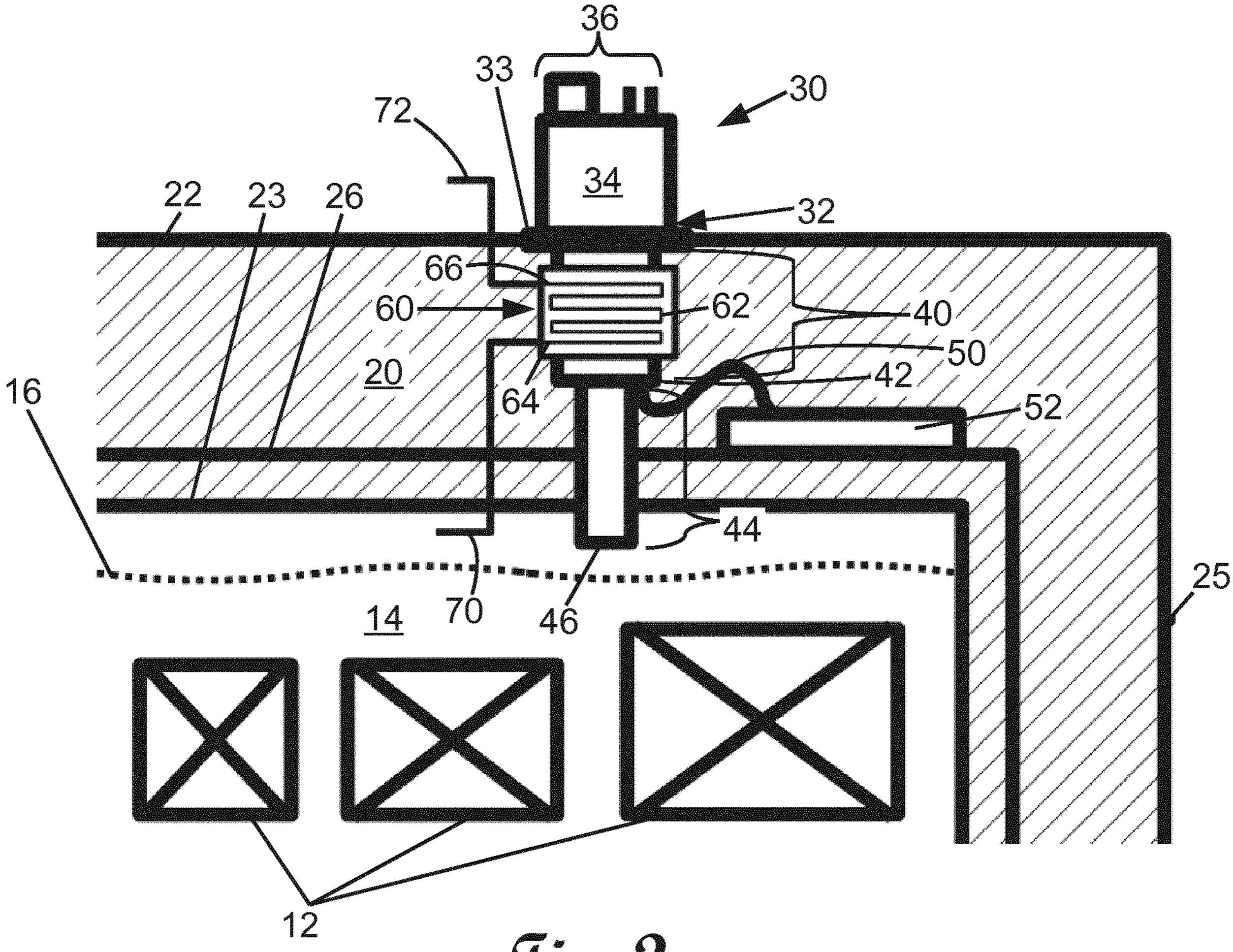
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Fig. 2

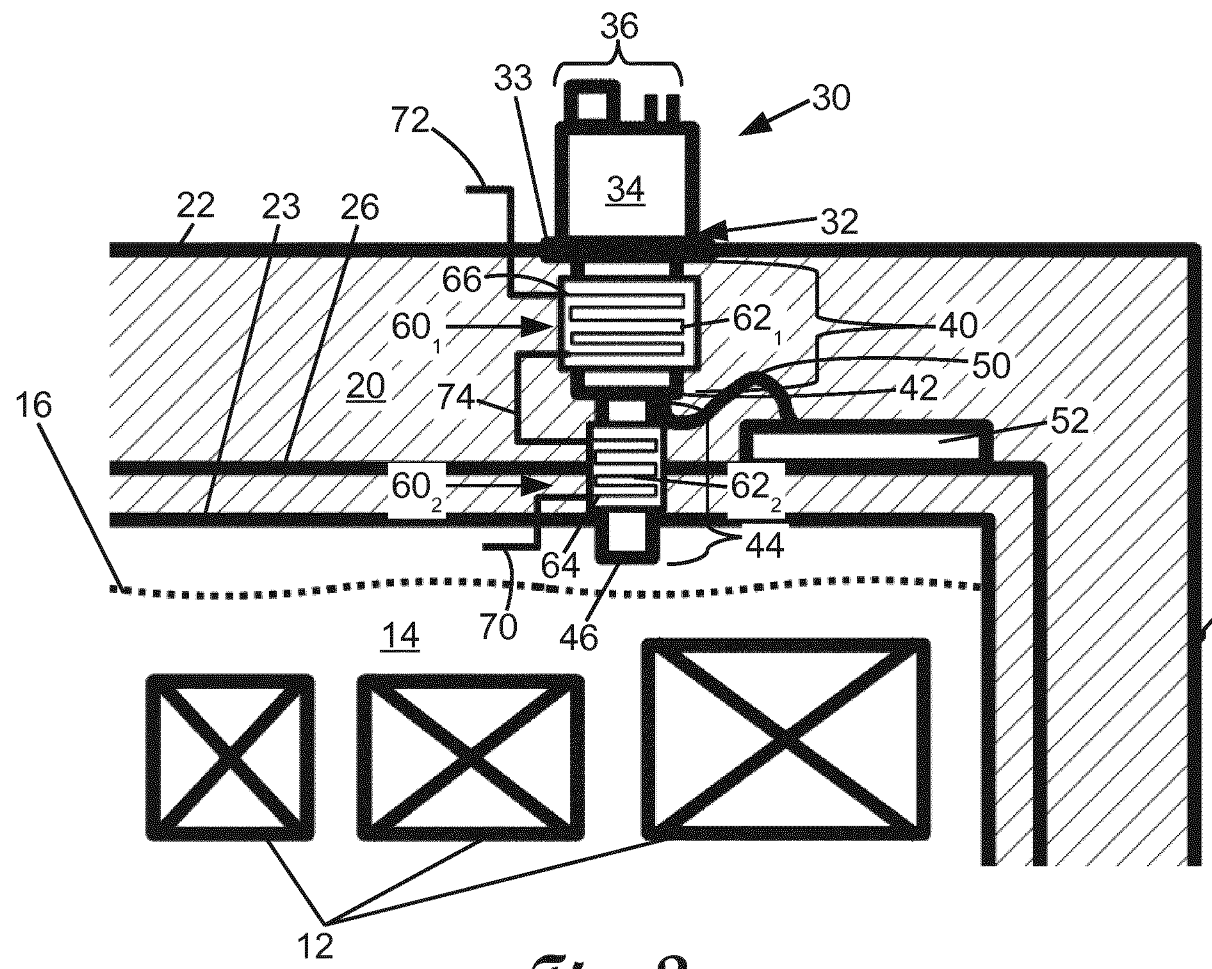
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Fig. 3

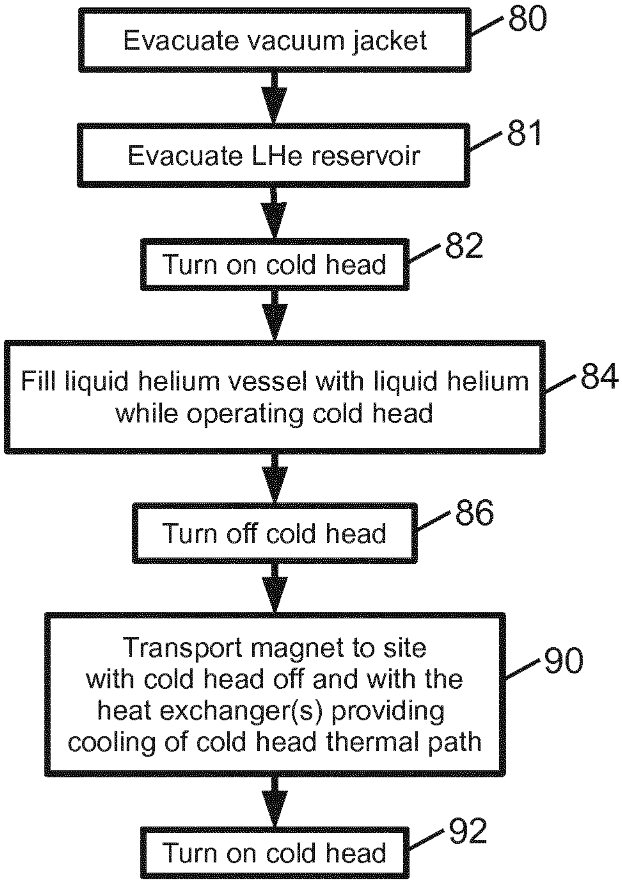
Evacuate vacuum jacket
80
Evacuate LHe reservoir
81
Turn on cold head
82
Fill liquid helium vessel with liquid helium while operating cold head
84
Turn off cold head
86
Transport magnet to site with cold head off and with the heat exchanger(s) providing cooling of cold head thermal path
90
Turn on cold head
92

Fig. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/069343

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01F6/04
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 015 728 A1 (AIR PROD & CHEM [US]) 17 September 1980 (1980-09-17) page 1; claim 1; figure 1	1-20
X	EP 0 131 652 A2 (AIR PROD & CHEM [US]) 23 January 1985 (1985-01-23) page 2; figure 1	1-20
A	WO 2010/032171 A1 (KONINKL PHILIPS ELECTRONICS NV [NL]; KAGAN ALEXANDER [US]; REIS CHANDR) 25 March 2010 (2010-03-25) page 3 - page 4	12
A	EP 3 016 156 A1 (JAPAN SUPERCONDUCTOR TECH [JP]) 4 May 2016 (2016-05-04) paragraph [0099]; figure 16 paragraph [0089] - paragraph [0091]	2,16

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 October 2018	31/10/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Rouzier, Brice

2

Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	GB 2 492 645 A (BRUKER BIOSPIN AG [CH]) 9 January 2013 (2013-01-09) abstract; figure 5 -----	1,13,15

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2018/069343

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0015728 A1	17-09-1980	DE 3067731 D1	14-06-1984
		EP 0015728 A1	17-09-1980
		US 4223540 A	23-09-1980
EP 0131652 A2	23-01-1985	CA 1118680 A	23-02-1982
		DE 3072010 D1	24-09-1987
		EP 0021802 A2	07-01-1981
		EP 0120131 A1	03-10-1984
		EP 0131652 A2	23-01-1985
		US 4277949 A	14-07-1981
WO 2010032171 A1	25-03-2010	CN 102160131 A	17-08-2011
		EP 2332153 A1	15-06-2011
		JP 2012503323 A	02-02-2012
		RU 2011115817 A	27-10-2012
		US 2011179808 A1	28-07-2011
		WO 2010032171 A1	25-03-2010
EP 3016156 A1	04-05-2016	CN 105340095 A	17-02-2016
		EP 3016156 A1	04-05-2016
		JP 6084526 B2	22-02-2017
		JP 2015007585 A	15-01-2015
		US 2016369946 A1	22-12-2016
		WO 2014208512 A1	31-12-2014
GB 2492645 A	09-01-2013	CH 705269 A2	15-01-2013
		DE 102011078608 A1	10-01-2013
		GB 2492645 A	09-01-2013
		US 2013008187 A1	10-01-2013